P4.5 FLOW AND REGIME DEPENDENT MESOSCALE PREDICTABILITY

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1. Introduction

Although the synoptic-scale evolution of the typical midlatitude weather system is relatively well-forecasted, numerical weather prediction models still have difficulties in forecasting the "mesoscale details" which are of most concern to the typical user of the model's forecast. It is of great interest to assess the predictability of these mesoscale weather systems, particularly with respect to the amount and spatial distribution of the associated precipitation. This study seeks to estimate the predictability of mesoscale features embedded within different synoptic-scale flow regimes and to identify key physical processes that control the limit of predictability at the mesoscale through sensitivity experiments of idealized moist baroclinic waves and case studies of high-impact weather events.

The NCAR-PSU MM5 (Duhdia 1993) is used for this current study. The initial and boundary conditions for the simulations of the observational cases come from the NCEP and ECMWF global reanalysis datasets archived at NCAR. The model domains, at least on the coarse grid where the initial perturbations are introduced, will be sufficiently large so that the region of interest will be far away from the unperturbed lateral boundaries to keep the error reduction due to the "sweeping" effect (e.g., Vukicevic and Errico 1990) at a minimum for forecasts up to 2 days. The MM5-based procedure to create balanced initial conditions for simulating idealized moist baroclinic waves is detailed in Tan et al. (2004). This procedure includes using 3-dimensional potential vorticity (PV) inversion technique to invert the balanced finite amplitude baroclinic waves from specification of the background 3-D PV field. Details on the model configurations and experimental design for the simulations discussed below can be found in Tan et al. (2003), Zhang et al. (2003; hereafter ZSR03) and Zhang et al. (2004).

We focus primarily on the intrinsic mesoscale predictability in which the forecast model is assumed to faithfully represent the dynamics of the atmosphere and only small initial perturbations will be introduced.

2. Mesoscale predictability of winter cyclones

We have recently explored the growth of small-scale differences in the surprise East Coast snowstorm of 24–25 January 2000 through explicitly calculating the difference evolution between a control simulation of MM5 and a simulation from perturbed initial conditions (ZSR03). In the perturbed experiments, a small-scale monochromatic temperature perturbation of 85-km wavelength is added. Forecast sensitivity to the small-scale small-amplitude initial errors has been examined through integrations of 30-km simulations in which moist convection is parameterized and triply nested simulations in which moist convection is explicitly resolved on the innermost 3.3-km grid. At either resolution, differences grow rapidly at scales of 100–200 km over the first 6 h and then, over the next 12 h, spread to larger scales while their growth slows.

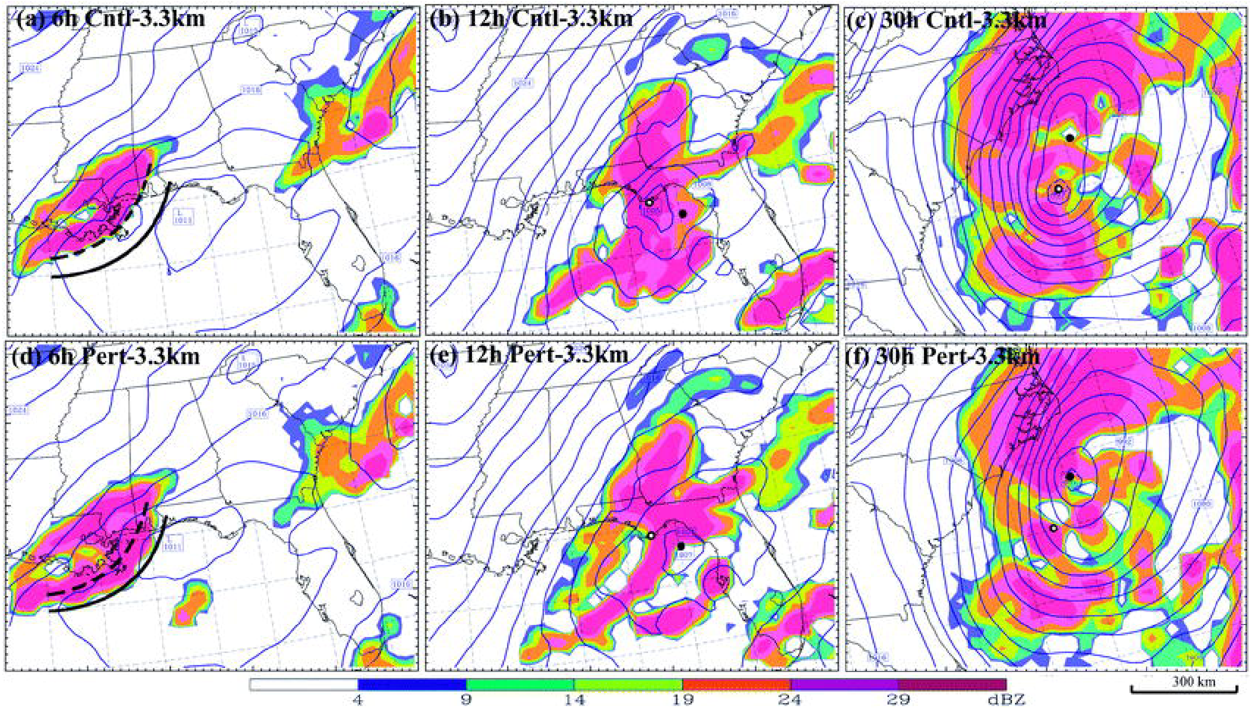

Figure 1. Comparison of mean sea level pressure (contour interval 4 hPa) and simulated reflectivity (dB*Z*, colored) on the 30-km grid for Cntl-3.3km and Pert-3.3km. Simulations are shown at (a), (d) 6 h, (b), (e) 12 h, and (c), (f) 30 h. Thick curves in (a) and (b) denote the relative locations of the convective outflow boundary in Cntl-3.3km (dashed) and Pert-3.3km (solid). The dots in (b), (c), (e), and (f) denote the locations of the primarily surface cyclone centers in Cntl-3.3km (open dots) and Pert-3.3km (solid dots) (Refer to ZSR03 for details).

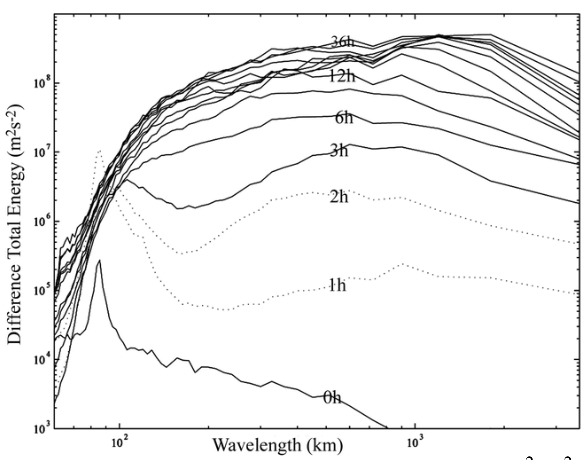

Figure 2. Power spectra of the DTE (in m^2 s^{-2}) between Cntl-3.3km and Pert-3.3km plotted every 3 h (Reproduced from ZSR03).

Figure 1 shows the mean sea level pressure and reflectivity at the 6-, 12-, and 30-h forecast times from the unperturbed (Cntl-3.3km) and perturbed (Pert-3.3km) simulations, respectively. The power spectrum of difference total energy between these two high-resolution experiments is displayed in Fig. 2. Both figures (as well as other diagnosis discussed in ZSR03) demonstrate that the error growth occurs initially on a timescale of about an hour and is associated with differences in the timing and location of individual convective cells (due to convective instability). Upscale spreading of differences with time is evident both in physical and spectral representations of the differences; the upscale error growth in these high-resolution experiments are significantly stronger than the lower-resolution experiment with parameterized convection. After 24-30 h, differences are significantly influenced by balanced dynamics and have begun to appear in, for example, the subsynoptic-scale structure of the surface low. It is demonstrated that moist convection is a primary mechanism for forecast-error growth at sufficiently small scales, and that convective-scale errors contaminate the mesoscale within lead times of interest to NWP, thus effectively limiting the predictability of the mesoscale, much as foreseen by Lorenz (1969).

In real time, the "surprise" snowstorm of 24-26 January 2000 has very limited predictability at all scales for operational forecast models. Results from this single case of midlatitude cyclogenesis are then reexamined for the "Storm of the Century (SOC)" of March 1993, which is one of the most successful heavy snow and blizzard forecasts ever for a major winter storm in real time (Uccellini et al. 1995). Preliminary sensitivity experiments of the SOC, performed similarly to ZSR03, suggested that the error growth rate in the "SOC" is indeed smaller than that in the "surprise" snowstorm of 2000 (not shown). Ongoing efforts are to determine the key differences in the flow regime between these two major explosive extratropical cyclogenesis events which lead to the apparent different predictability behavior.

3. Mesoscale predictability of an extreme warm-season flooding event

We also examined the warm-season mesoscale predictability of an extreme flooding event in central-south Texas of July 2002. On 29 June 2002, a heavy rainfall event was initiated over central Texas that lasted through 7 July 2002 with the heaviest precipitation dropped near San Antonio, Texas area. Several counties in the Edwards Plateau and South Central regions received excessive amounts of precipitation, causing flooding, millions of dollars in damage and loss of life. Operational models used at NCEP had forecasted some heavy precipitation in the area, but the timing, duration and intensity of heavy precipitation were not well forecasted in real time. This warm-season event is subtropical in nature with strong conditional instability but weak baroclinicity, and stands in strong contrast to mid-latitude extratropical cyclones with strong baroclinicity. The persistence of moist convective precipitation over the same basic area for 8 days makes it an ideal case for assessing mesoscale predictability. We have found that similar kinds of damaging extreme warm-season flooding events occurred more than 10 times over Texas over the past half century (Nielsen-Gammon et al. 2004).

Sensitivity experiments are performed similar to ZSR03 except for using a 0.2-K grid-point random perturbation to the initial temperature field. Similar to ZSR03, it is shown that there is rapid error growth due to strong moist instability shortly after the perturbations are introduced, both in integrations of 30-km simulations in which moist convection is parameterized and triply nested simulations in which convection is explicitly resolved on the innermost 3.3-km grid. Virtually no error growth occurs between two "fake-dry" experiments (no latent heating release, effectively without the impact of moist convection) (Fig. 3).

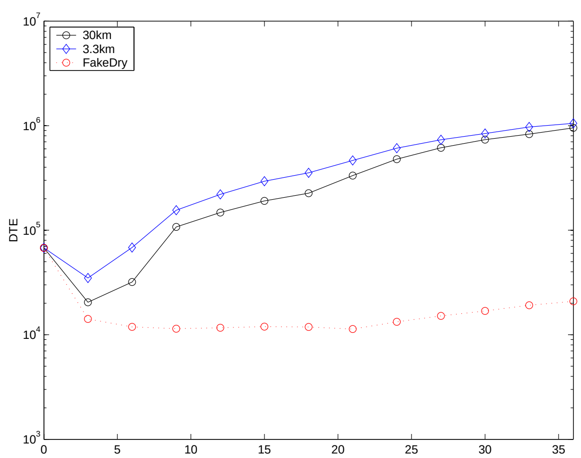

Figure 3. Evolution of difference total energy (DTE, m^2s^{-2}) for between 30- and 3.3-km experiments with full moist physics and 30-km fake-dry experiments.

Also similar to ZSR, rapid error growth from small-scale small-amplitude initial error can significantly contaminate the short-term deterministic mesoscale forecast, especially precipitation (not shown). Moist convection is again crucial to mesoscale predictability. Note that the initial error decay seen in all experiments (Fig. 3) is due to model diffusion and adjustment to remove error energy in the unresolved scales presented in the random and unbalanced initial perturbations all across the model domain, even though there is rapid error growth over areas of localized convection.

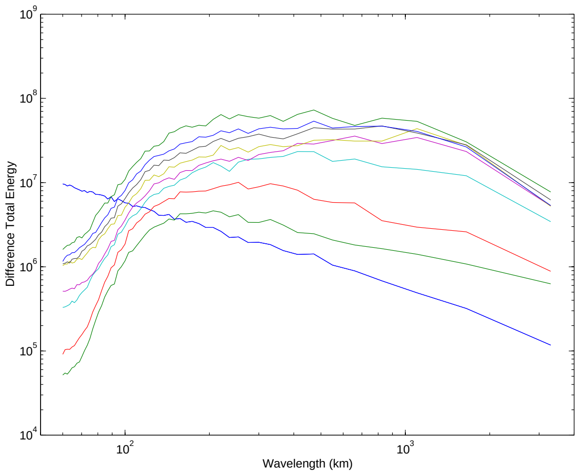

Figure 4. Power spectrum of the difference total energy (DTE, m^2s^{-2}) between perturbed and unperturbed 30-km simulations plotted every 3 h.

However, compared to that of the snowstorm of January 2000, the upscale error growth is relatively weak and thus has relatively smaller impacts on larger scales (Fig. 4). In contrast to the results of ZSR03, error grows faster only initially in 3.3-km high-resolution simulations but "saturated" at similar amplitude compared to the 30-km lower resolution simulations. Difference between error-growth dynamics in the warm-season mesoscale weather and the mid-latitude baroclinic weather systems further suggests that mesoscale predictability is flow and regime dependent, even though similar dynamical processes that limit the mesoscale predictability of the mid-latitude baroclinic weather systems may constrain that of the warm-season mesoscale predictability. Importance of flow-dependent predictability was also discussed in Tracton (1990) and Nuss and Miller (2001).

4. Mesoscale predictability of idealized moist baroclinic waves

Results from individual case studies are generalized through examination of error growth dynamics in an idealized baroclinic wave amplifying in a conditionally unstable atmosphere (refer to Figs. 1-2 of Tan et al. 2004). Consistent with the aforementioned case studies, the 30-km low-resolution experiments with parameterized moist convection show that without the effects of moisture, there is little error growth in the short-term (0-36 h) forecast error (starting from random noise), even though the basic jet used here produces a rapidly growing synoptic-scale disturbance. With the effect of moisture included, the error is characterized by upscale growth, similar to that found in the study of the numerical prediction of the "surprise" snowstorm (Fig. 3 of Tan et al. 2004). It is also demonstrated that the higher the moisture content, which implies stronger conditional instability, the stronger the error growth (Fig. 5).

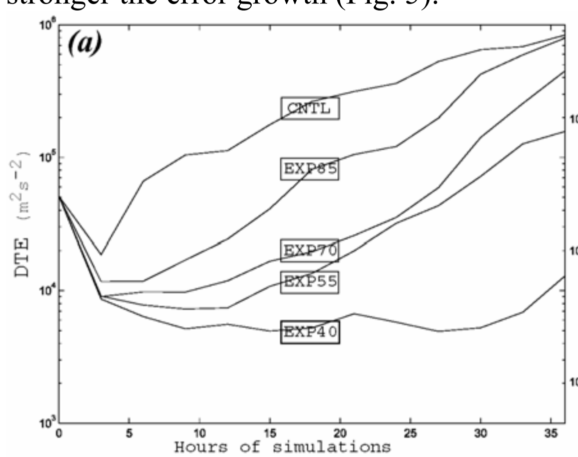

Figure 5: Evolution of difference total energy (DTE, m^2s^{-2}) for between 30- experiments with initial moisture content. The relative humidity in EXP85, EXP70, EXP55 and EXP40 is 85%, 70%, 55% and 40% of that in CNTL (from Tan et al. 2004).

Multigrid-nesting convective-resolving simulations are also performed to extend the low-resolution results from Tan et al. (2004) to the 3.3-km innermost grid, which explicitly resolves moist convection, covers a domain of 1833 km by 1333 km and is integrated for 9 h after the random perturbations were introduced. Consistent with ZSR03, even faster error growth with stronger upscale spreading are observed in these high-resolution simulations. The 5-km AGL vertical velocity fields from both perturbed and unperturbed simulations at 3 h are displayed in Fig. 6. After 3 h of integrations, individual convective cells with maximum updraft greater than 30 m/s are randomly triggered everywhere along the frontal squall line. Even though the positioning of the squall line are nearly the same in both simulations, identities and locations of individual cells differ greatly. At 9h, we begin to observe a systematic shift of the squall line, signaling apparent upscale error growth (Fig. 7). It is worth noting that additional perturbed high-resolution (3.3-km) experiments with the same initial random perturbation amplitude but with different realizations show that the difference in the frontal squall line position of is smaller between two perturbed runs than the difference between perturbed and unperturbed runs, suggesting initialization of high-resolution grids with smoothed coarse-domain data contributes to the divergence of the forecast solutions in Figs. 6-7 as well.

There are also significant differences between the error-growth characteristics obtained from the observed event in ZSR03 and those from the idealized study of idealized baroclinic waves: Over a 36-h model integration with initial errors of similar amplitudes, the error growth in the idealized baroclinic waves, as measured by the domain averaged difference total energy, is much smaller than that found in the "surprise" storm of January 2000. Consistent with our hypothesis from the real case studies discussed above, this apparent discrepancy between the idealized waves and observed event suggests that there are other factors other than moist convection and the background baroclinicity that control the limit of mesoscale predictability. It could have been the effects of surface and

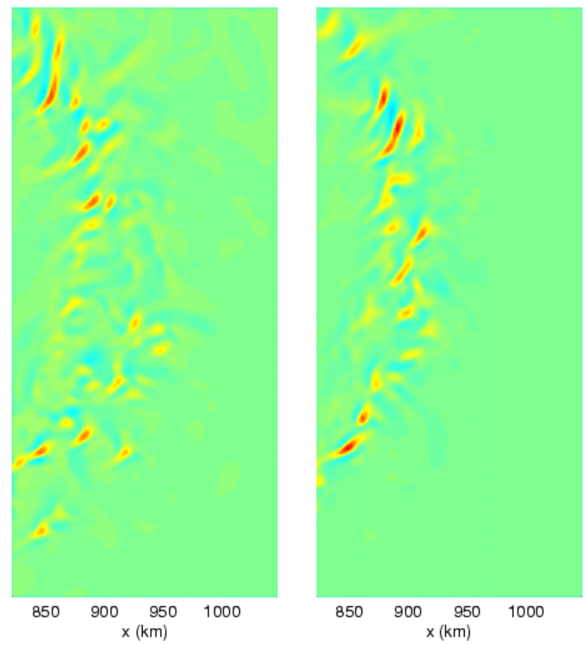

Figure 6. The 5-km AGL vertical velocity (colored; red, updraft; blue, downdraft) from the 3.3-km perturbed (left) and unperturbed (right) simulations after 3 h of integration.

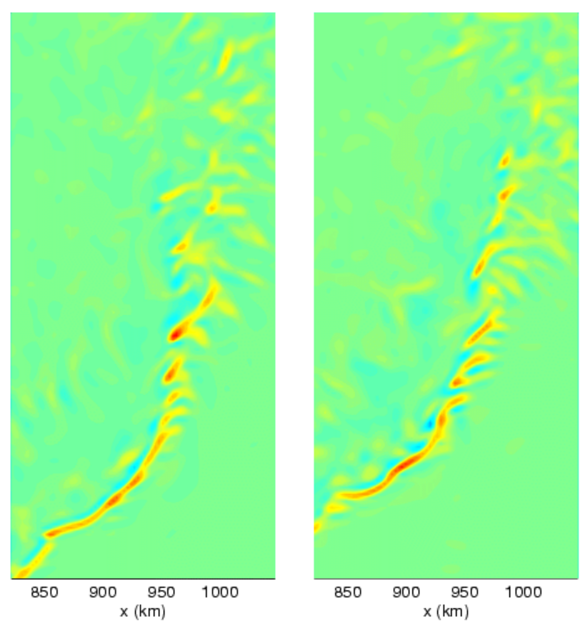

Figure 7. As in Fig. 6 but after 9 h.

boundary layer inhomogeneities including the land-ocean contrast and topography which are not included in the idealized study. It could also be due to difference in baroclinicity or static stability of the large-scale background flows. Future work will examine error growth sensitivity to different flow configurations of moist baroclinic waves including sensitivity to the 2-D jet strength, Coriolis force, surface temperature gradient, and static stability.

5. Concluding remarks

In this study, through sensitivity experiments of idealized moist baroclinic waves and case studies of high-impact weather events, we have begun to demonstrate the flow- and regime-dependent nature of intrinsic mesoscale predictability. It is hypothesize that moist processes (especially moist convective instability) impose fundamental limit on mesoscale predictability but the error-growth dynamics is strongly dependent on the background flow and its associated larger-scale dynamics or instability.

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